Optimization of Fatigue Strength of Welded Rotationally Symmetrical Components by Surface Strengthening of Welding Zone

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1. Summary

Dynamic component tests are integral part of innovative development projects in numerous application ranges of automotive supply industry. In this contribution comparative studies of so-called ball studs (Fig. 1) are put up for discussion. Emphasis of analysis refers to rotationally symmetrical welded components. By the use of destructive material testing new findings should be gained in order to optimize durability of ball studs in consideration of economical issues. Components have been tested to failure by means of high frequency pulser.

Figure 1: Ball stud as a model and in original, welded design

The fracture patterns (Fig. 2) show in all cases a crack propagation, which propagates from the weld zone into the cone. Mechanical methods for processing of the welding zone, for example by compaction rolls, as well as abrasive processes with subsequent polishing or blasting of the surface yielded not a positive result in terms of an increase of load. Only through a process of an additional hardening the surface of the welding zone could improve the number of load cycles by a **factor of 8-10**.

Figure 2: Fracture patterns of welded ball stud

Content

2. Introduction

The main applications of the tested ball studs are car-coupling rods (Fig. 3), which connect the stabilizer to the suspension strut.

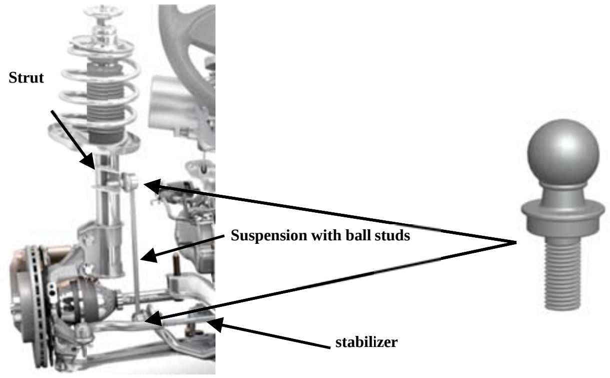


Figure 3: Example of a coupling rod [5] with ball stud

By default, ball studs are produced by cold forming of the blank followed by further processing. The first step of post-processing is a shape turning process to get the final contour of the ball stud. The second step is a surface treatment process i.e. ball is work hardened by spinning operation and roughness is reduced. Further still notch effects are present by the machining shape in the transition region between the ball and the shaft. Notching effect generally has a negative influence on flexural fatigue. Due to increased demands in recent years in terms of design and load of ball studs, the question arose how to increase the number of cycles with unchanged geometries. After numerous tests, e. g. with high-tensile materials, work hardening of the welding zone or abrasive operations followed by polishing respectively blasting of the surface did not increase life time. Aim of the project was to develop a method realizing increase of life time of ball studs with specified geometry and flexural fatigue.

3. Fundamentals and Experimental procedure

As described in chapter 1, ball studs are manufactured by a cold forging process followed by several processes like turning, grinding and polishing. An alternative manufacturing process is the production of the base body by cold forging followed by a welding process, in which a ball of the base body is welded. The benefits of the welded version are better roughness of ball surface and the needlessness of post-machining, because basic bodies as well as the ball already have their final shape. Since more than ten years ball studs in welded version have been successfully applied. Increasing customer requirements within the scope of several „Downsizing"– projects forced the geometrical boundary conditions to be adapted. Regardless of the geometric changes, for example a smaller ball diameter and / or smaller shaft design, the load requirements are increased. For these reasons a project has been initiated in order to compile a feasible and economical solution.

4. Typical stress type for ball studs

Ball studs usually are subjected by bending. This means that, first and foremost bending forces may be applied. Theoretical calculations based on the FKM or DIN 743 and a first fracture mechanics analysis of stress intensity factors have shown that the example of our welded ball stud meets the criterion for a crack growth. The result of the calculations [1-4] shows that $\Delta K > \Delta K_0$, which explained a crack growth. Hereinafter, the test results are displayed, showing the results available for the required load. For test procedure a high-frequency pulser from „ Zwick-Roell“ is used. Frequency of pulser is between 50 and 70 Hz. Fig. 4 shows the fixing unit for seating the specimen.

12	Prüfmutter – Güte 10
11	Schraube M6x30 – 8.8
10	Schraube M10x40 – 8.8
9	Schraube M8x40 – 8.8
8	Unterlegscheibe
7	Kugelbolzen
6	Kugelpfanne
5	Distanzscheibe
4	Spannscheibe
3	Prüfeinsatz
2	Gewindeaufnahme
1	Prüfaufnahme

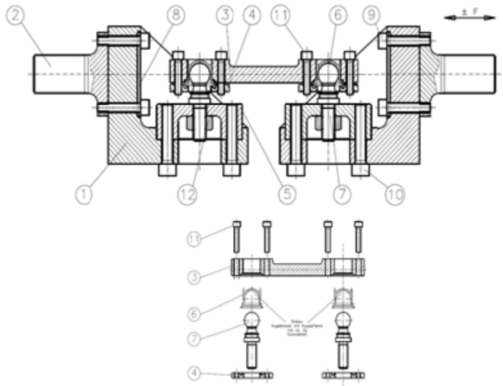
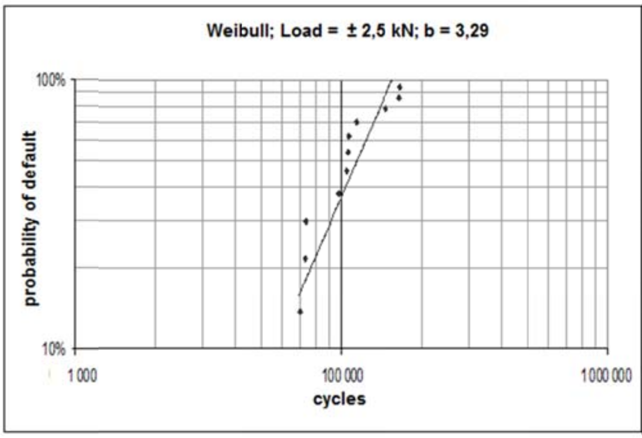


Figure 4: Pulser with ball mount for the simulation of a coupling rod connection

5. Experimental Procedure

The first test run has been conducted for ball studs with a reworked welding zone. The rework has been considered purposive in order to reduce the notching effect in the weld zone’s transition area between ball and stud. The Customer’s requirement was a repeated load of ± 2,5 kN with a stress ratio of R = -1 and at least 200.000 load cycles. Figure 5 (right hand side) is showing the numbers of cycles to failure of the tested ball stud. The individual cycles results were then transferred into a Weibull (Fig. 5, left). Subsequently the specific
load cycle results have been transferred into a Weibull diagram (Figure 5 left hand side).



Load = ± 2,5kN, R = -1	
	Cycles
N	Ball studs with turened welding zone
1	69 290
2	70 060
3	73 240
4	73 525
5	97 280
6	104 360
7	106 015
8	106 380
9	113 800
10	146 525
11	164 460
12	165 800

Figure 5: Weibull and experimental results with turned and polished welding zones

The requirement of at least 200.000 load cycles has not been fulfilled. Now it was necessary to think about further options to increase the fatigue strength of the ball studs. The result was the utilization of residual compressive stresses in the transition area between the ball and the shaft. The hardening of the edge layer, especially in the welding zone area, has been realized by induction hardening (Fig. 6). Alternative processes like laser hardening or nitrogen hardening were out of the question either for financial or for technical reasons.

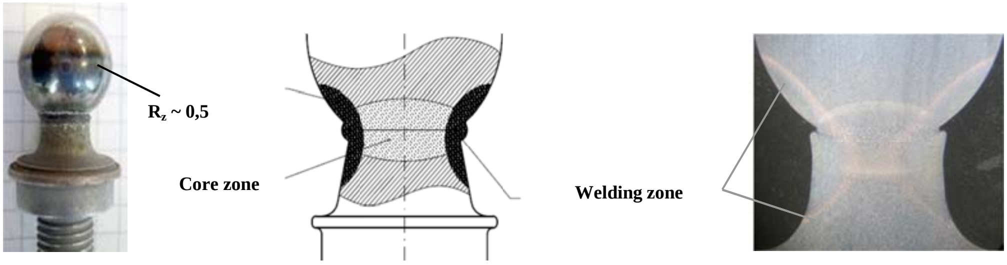
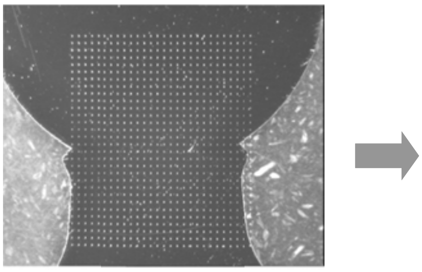


Figure 6: Result of inductive surface hardening (discolor the ball (left), model the heat affected zone (center), cut (right))

In an additional step the measurement of micro hardness of heat affected zone has been conducted in order to evaluate ratio between edge layer hardness and core hardness.
On the left hand side on figure 7 shows the result of measured position. On the right hand side on figure 7 illustrates the results of micro hardness measurement; edge layer area ≈ 550 HV; core area ≈ 350 HV.



315	329	330	326	338	321	337	330	344	353	326	332	334	329	333	341	326	332	334	304	328	326	308	305	314	321	320	308
315	314	322	325	322	312	320	329	326	330	326	333	320	326	312	336	337	329	330	320	315	322	316	311	315	314	303	302
304	308	309	303	317	317	317	326	324	321	337	324	329	333	317	311	320	309	325	312	320	312	310	309	290	308	302	294
290	306	315	311	315	317	320	320	316	316	326	322	315	310	306	301	325	315	310	310	310	299	305	303	299	290	290	289
294	288	303	305	316	308	306	312	316	299	317	304	317	309	310	306	316	303	314	299	303	295	293	291	296	291	283	333
291	283	289	301	305	305	311	305	309	306	312	308	314	317	310	296	306	293	288	296	298	296	293	298	291	291	340	407
283	278	289	287	299	299	301	305	298	285	305	310	310	308	295	309	312	311	305	298	295	290	291	282	294	350	391	474
350	287	288	286	288	296	283	293	296	303	291	298	296	301	295	290	297	298	291	283	293	289	290	305	357	412	508	548
382	351	310	282	287	291	291	293	301	296	285	301	287	287	280	291	285	284	287	287	279	284	330	353	391	442	523	560
442	394	347	315	287	285	289	285	290	288	291	288	289	286	290	288	285	284	281	282	287	330	365	389	454	523	566	553
465	389	360	341	321	299	282	281	273	284	285	286	285	287	283	281	287	282	287	298	334	359	401	458	526	560	554	543
545	474	391	337	333	312	302	281	280	280	274	280	281	284	277	279	286	295	320	334	351	379	420	486	540	545	537	545
551	534	474	405	350	324	310	303	289	273	258	254	258	253	253	265	280	294	308	345	356	382	446	505	534	554	548	557
551	534	523	463	407	373	343	317	315	319	321	314	297	302	308	317	319	334	347	350	373	437	500	537	537	545	543	554
540	537	534	513	461	431	398	379	373	348	341	337	330	328	333	345	356	376	398	415	452	491	540	557	543	543	540	
548	543	526	523	491	467	429	418	398	387	382	387	365	373	374	376	387	403	424	435	474	508	540	537	551	563		
554	551	545	548	521	472	442	414	347	386	384	401	387	382	393	398	422	410	427	437	476	503	540	551	474	638	563	
532	563	572	578	467	437	420	382	368	368	368	376	353	365	365	374	376	387	401	444	516	578	557	540	529	529	545	
534	518	526	537	510	491	446	424	389	394	360	365	362	360	376	362	376	400	412	458	495	540	529	529	532	529	526	
521	526	526	518	532	516	461	435	386	354	353	344	344	356	347	344	359	401	429	465	513	543	537	540	529	537		
534	526	523	521	532	510	461	424	389	356	353	340	343	334	348	354	379	376	405	433	491	548	545	534	543	545		
543	526	523	518	523	505	424	379	334	328	341	325	320	315	334	333	353	351	377	396	450	521	548	537	523	543		
534	523	521	516	510	452	389	362	316	295	297	295	282	275	290	289	305	324	350	384	427	483	537	523	521	526		
540	526	516	526	500	456	377	351	320	304	304	280	289	279	281	284	309	312	330	359	386	454	513	532	518	529		
537	532	523	505	448	420	357	330	304	286	279	265	265	254	265	263	290	303	314	328	363	426	479	518	529	540	486	
529	529	523	483	420	381	328	305	276	266	256	258	250	255	263	259	263	272	284	305	343	376	427	486	508	529	563	
529	532	266	260	259	277	304	277	259	260	266	259	263	264	266	255	271	263	269	270	303	336	379	414	454	521	563	
540	495	426	389	341	309	273	259	263	259	266	263	263	269	273	262	271	269	269	267	271	294	329	363	407	448	500	
474	431	381	338	306	264	271	270	267	268	277	271	276	269	270	266	276	275	276	273	273	266	274	326	354	398	422	
414	381	332	290	267	276	271	273	273	272	278	271	284	272	280	275	280	282	285	279	272	283	271	274	281	328	360	373

Mesh (scale = 0,3 mm)
0,30
0,30
Not etched/ mesh overview

calibration before mesh=
Measures 760 751 755 755 760
Mean 756 HV0,5
probe value 764 HV0,5
calibration OK (difference sample vs probe)= -1%

Figure 7: Grid and hardness profile of the heat-affected zone

The edge layer hardened samples of ball studs have been tested with a high frequency pulser (2.5 kN 3.0 kN 3.5 kN, 4 kN) according to required test load data.
Because of the non-successful load cycles results, in accordance with customer requirement of ± 2,5 kN for ball studs with additional turning process of the welding zone, now edge layer hardened ball studs were tested with a load of ±2,5 kN.

Results of the initial test series are represented for comparison in table 1.

Table 1: Comparison of cycles "with additional turning process " and "Surface hardened"

Load = ±2,5 kN; R= -1		
	Cycles	Cycles
N	with additional turning process	surface hardened
1	69 290	1 000 000
2	70 060	1 000 000
3	73 240	1 500 000
4	73 525	1 500 000
5	97 280	1 500 000
6	104 360	1 500 000
7	106 015	2 000 000
8	106 380	2 000 000
9	113 800	3 000 000
10	146 525	3 000 000
11	164 460	5 000 000
12	165 800	5 000 000

For specified load of ± 2,5 kN there was no failure of components of edge layer hardened ball studs. The test series have been stopped correspondingly between one million and five million cycles. Individual results of ball studs with reworked welding zones as well as the results with edge layer hardened ball studs have been subsequently transferred into a Weibull- and Wöhler diagram. The Weibull-Diagram of the survival probability of edge layer hardened ball studs in comparison with ball studs without surface hardening (Fig. 8) shows that the survival rate was improved by the **factor 10**. By way of example we regard the range ± 3,5 kN (survival probability SP, grey and black line), illustrating this increase of load from 20.000 cycles to 200.000 cycles. According to Weibull-diagram the Wöhler-diagram in Fig. 9 also indicates a considerable improvement regarding fatigue strength under repeated load.

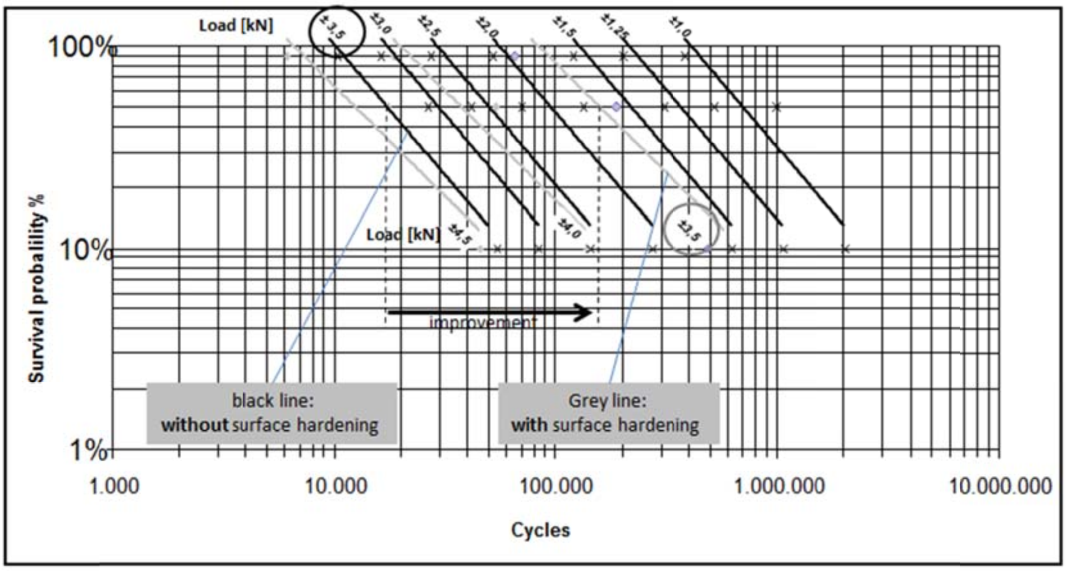


Figure 8: survival probability Weibull-diagram, comparison of ball studs without surface hardening (black line)/with surface hardening (gray line)

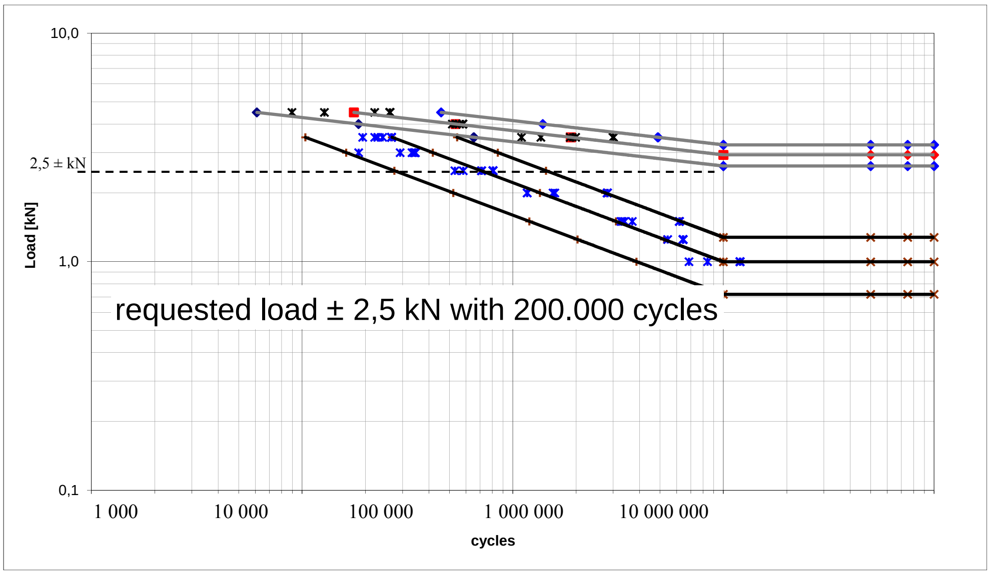


Figure 9: Wöhler diagram comparison ball stud without surface hardening (black line) / with surface hardening (gray line)

6. Conclusions and Outlook

In a further step the behavior of edge layer is to be analyzed by means of additional mathematical calculation and a FEM simulation of the welding zone.
Furthermore the dependency between the material, edge layer hardness/core hardness, depth of the edge layer hardening and the diameter ratio of the samples is to examined more closely. With this technical approach it should be possible to create an optimal design as a function of boundary conditions for similar products. Further tests are planed as well with aluminum casting parts to identify the properties of the welding zones in these parts and to improve the lifetime.

7. References

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